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Rate of Convergence of the Discrete Pólya-1 Algorithm*

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The rate of convergence of the discrete Pólya-1 algorithm is studied. Examples are given to show that the rates derived are sharp.

Let V be a finite dimensional subspace of $\mathbb{R}^n$ and fix $z \in \mathbb{R}^n \setminus V$. Given a norm, $\|\cdot\|$, on $\mathbb{R}^n$, $v^* \in V$ is a best approximation from V to z if

$$\|v^* - z\| = \min\{\|v - z\| : v \in V\}.$$

In this setting the existence of a best approximation is immediate. Of course, different norms may give rise to different best approximations. The dependence of best approximations on the norm in use has been studied in a variety of contexts. For example, [1] and [10] are general studies of the effects of perturbing the norm on best approximation problems.

The p-norms, given by

$$\|x\|_p = \left[\sum_i^n |x_i|^p\right]^{1/p}, \ 1 \leqslant p < \infty, \qquad \text{and} \qquad \|x\|_\infty = \max_i |x_i|$$

form a well-known parameterized family of norms on $\mathbb{R}^n$. Denote by l^p the space $\mathbb{R}^n$ with the p-norm. In the l^p family of Banach spaces, selecting a value of p corresponds to a choice of norm. Each such choice determines

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a different best approximation problem. Discussions of the relative merits of specific values of p date from the 18th century [2].

For $1 < p < \infty$ the corresponding p-norm is strictly convex, so that there is a unique solution to the best approximation problem for this p. Denote this solution by x^p. For $p = 1$ and $p = \infty$ solutions to this best approximation problem need not be unique. The problem of the dependence on p of best approximations has been extensively studied. Of particular interest has been the behavior of the arc x^p as $p \to \infty$. The taking of such a limit is referred to as the Pólya algorithm and was first considered by Pólya in a related setting [9]. In the subspace setting it is known that the Pólya algorithm converges and that in general the rate of this convergence is $O(1/p)$ [3, 4].

The behavior of the arc x^p as $p \to 1$ has also been studied [6–8, 12]. Taking this limit is known as the Pólya-1 algorithm. The Pólya-1 algorithm converges in a very general setting, including the subspace problem under consideration here. Aside from an example and a conjecture [4] little is known about the rate at which the Pólya-1 algorithm converges. In the following, the rate of convergence is developed. In contrast to the Pólya algorithm rate, it is shown that the rate of convergence of x^p depends heavily upon the set L of l^1 best approximations. To see this consider the following examples:

EXAMPLE 1. In $\mathbb{R}^3$, let $z = (0, 0, 1)$ and let $V = \{(a, a, a) : a \in \mathbb{R}\}$. Here the l^1 best approximation is unique and is the median $(0, 0, 0)$. To find x^p, there is no point in considering $a > 1$ or $a < 0$. So we minimize $2a^p + (1-a)^p$ over $[0, 1]$. Differentiating gives $2a^\delta - (1-a)^\delta = 0$, where $\delta = p - 1$. Thus $(1-a) = 2^{1/\delta}a$ or $2^{-1/\delta} = a/(1-a)$. For p near 1, $\frac{1}{2} \leqslant 1 - a \leqslant 1$, so $a = O(2^{-1/\delta})$. Thus $x^p \to x^1$ at an exponential rate.

When the set L is not a singleton, a slower rate of convergence may hold.

EXAMPLE 2. In $\mathbb{R}^4$, let $z = (2, 1, 0, 0)$ and $V = \{a(1, 1, 1, -1) : a \in \mathbb{R}\}$. Here $L = \{a(1, 1, 1, -1) : a \in [0, 1]\}$. Consider the strict best approximation $x^1 = a^1(1, 1, 1, -1)$, the limit of x^p as $p \to 1$. On L, a^1 minimizes $\psi(r) = (2-r)\ln(2-r) + (1-r)\ln(1-r) + 2r\ln(r)$. (See Theorem 1.) Now $\psi'(r) = 2\ln(r) - \ln\{(2-r)(1-r)\}$, yielding critical values 0, 1, and $\frac{2}{3}$. Since x^1 lies in the relative interior of L [6], $a^1 = \frac{2}{3}$. Write $x^p = a^p(1, 1, 1, -1)$. Since $x^p \to x^1$, we know that for small $p > 1$, $\frac{1}{2} < a^p < \frac{7}{9}$. Note that for values of r between 0 and 1, $\psi_p(r) = \|z - r(1, 1, 1, -1)\|_p^p = (2-r)^p + (1-r)^p + 2(r)^p$. Then $\psi_p'(r) = -p((2-r)^\delta + (1-r)^\delta - 2(r)^\delta)$, where $\delta = p - 1$. Then $\psi_p'(\frac{2}{3}) = -p((\frac{4}{3})^\delta + (\frac{1}{3})^\delta - 2(\frac{2}{3})^\delta) = -p3^{-\delta}(2^\delta - 1)^2 < 0$. This forces $a^p > \frac{2}{3}$ for small $p > 1$. Thus, for small p, $2 > p > 1$, $\frac{7}{9} > a^p > \frac{2}{3}$.

Therefore, for such small $p>1$, we may write $a^p=\frac{2}{3}+\varepsilon_p/3$, where $0<\varepsilon_p<\frac{1}{3}$. Hence ε_p satisfies

$$\begin{aligned}((4-\varepsilon_p)/3)^\delta + ((1-\varepsilon_p)/3)^\delta - 2((2+\varepsilon_p)/3)^\delta \\ = 0 = (4-\varepsilon_p)^\delta + (1-\varepsilon_p)^\delta - 2(2+\varepsilon_p)^\delta.\end{aligned}$$

Thus, $4^\delta-(4-\varepsilon_p)^\delta+1-(1-\varepsilon_p)^\delta+2(2+\varepsilon_p)^\delta-2(2^\delta)=(2^\delta-1)^2$. Now apply the Mean Value Theorem individually to the expressions $(4-x)^\delta$, $(1-x)^\delta$, $(2+x)^\delta$, and 2^x all centered at $x=0$ to get constants c_i, $4-\varepsilon_p<c_1<4$, $1-\varepsilon_p<c_2<1$, $2<c_3<2+\varepsilon_p$, and $0<c_4<\delta$ such that

$$\delta\varepsilon_p(c_1^{\delta-1}+c_2^{\delta-1}+c_3^{\delta-1})=(\delta 2^{c_4}\ln 2)^2.$$

Thus, $\varepsilon_p=\delta 2^{2c_4}(\ln^2 2)(c_1^{\delta-1}+c_2^{\delta-1}+c_3^{\delta-1})^{-1}$ and there exist positive constants A and B such that $A\leqslant 2^{2c_4}(\ln^2 2)(c_1^{\delta-1}+c_2^{\delta-1}+c_3^{\delta-1})^{-1}\leqslant B$ for p in this range. Hence $4A\delta\leqslant\|x^p-x^1\|_1\leqslant 4B\delta$ for small $p>1$. Thus, x^p converges linearly to x^1 as $p\to 1$.

We now show that this dichotomy in rates holds in general. As above, denote by L the set of all l^1 best approximations from V to z. For $r\in\mathbb{R}$, we know that $r\ln(r)\to 0$ as $r\to 0^+$. Hence we identify $(0\ln(0))$ with 0 and, for $x\in\mathbb{R}^n$, define the function $\psi(x)$ by

$$\psi(x)=\sum_{i=1}^n |x_i-z_i|\ln|x_i-z_i|.$$

The limiting behavior of the net $\{x^p: p>1\}$ is described in the following theorem.

THEOREM 1. [6, 8, 12]. *Under the above hypotheses, there exists* $v\in L$ *such that* $\lim_{p\to 1}x^p=v$. *Furthermore,* v *is in the relative interior of* L *and is the unique minimizer of* ψ *on* L.

The element v is known as the *natural best approximation* or the *strict best approximation* of $z\in\mathbb{R}^n$ from V. Our interest is in the rate at which the best l^p approximations converge to the natural best approximation. Since this rate is unaffected by translation and scaling, we assume that $v=0$ and that $\|z\|_\infty<1/2e^2$ holds. Define $\Omega=\{i: z_i=0\}$. The following lemmas describe the zero structure of vectors near $v=0$.

LEMMA 1. *If* $v\in L$ *and* $i\in\Omega$ *then* $v_i=0$.

LEMMA 2. *For some* $\rho>0$ *and* $\varepsilon>0$, *the set* $W=\{x\in\mathbb{R}^n: \|x\|<\rho\}$ *has the following property: For* $x\in W$ *and* $i\notin\Omega$, $|x_i-z_i|>\varepsilon$ *and* $\operatorname{sgn}(z_i-x_i)=\operatorname{sgn}(z_i)$.

Lemma 1 follows from the minimality of $\psi(0)$ on L. Suppose $v \in L$ and $v_i \neq 0$ for some $i \in \Omega$. Then for sufficiently small λ, we would have $\lambda v \in L$ and $\psi(\lambda v) < \psi(0)$. This contradicts Theorem 1. Lemma 2 is a simple consequence of the continuity of each coordinate as a function of x.

The smoothness and strict convexity of the p-norms, $1 < p < \infty$, yield well-known uniqueness and characterization results for the corresponding l^p best approximation problems. While the 1-norm is not smooth, it does possess one-sided directional derivatives [11]. For x and $y \in \mathbb{R}^n$, $\|y\|_1 = 1$, define

$$D_y(x) = \lim_{t \to 0^+} \frac{\|x + ty\|_1 - \|x\|_1}{t}.$$

$D_y(x)$ is well defined for each such x, y pair and has the explicit formulation

$$D_y(x) = \sum_{S^c} \operatorname{sgn}(x_i)\, y_i + \sum_{S} |y_i|,$$

where $S = S_x = \{i : x_i = 0\}$ and S^c denotes the complement of S in $\{1, ..., n\}$.

Consider $w \in W \cap L$. By Lemmas 1 and 2, $w_i = 0$ for $i \in \Omega$ and $\operatorname{sgn}(z_i - w_i) = \operatorname{sgn}(z_i)$ for $i \notin \Omega$. Hence

$$\begin{aligned} D_v(z - w) &= \sum_{i \notin \Omega} \operatorname{sgn}(z_i - w_i)\, v_i + \sum_{i \in \Omega} |v_i| \\ &= \sum_{i \notin \Omega} \operatorname{sgn}(z_i)\, v_i + \sum_{i \in \Omega} |v_i| = D_v(z). \end{aligned}$$

This gives:

LEMMA 3. *Let $w \in W \cap L$ and $v \in \mathbb{R}^n$. Then $D_v(z - w) = D_v(z)$.*

For $v \in L$, Lemma 1 requires that $\operatorname{supp}(v) \subseteq \Omega^c$. The following lemma provides a partial converse.

LEMMA 4. *Suppose that $v \in V$ and* $\operatorname{supp}(v) \subseteq \Omega^c$. *Then $\lambda v \in L$ for small $\lambda > 0$.*

Proof: There is no loss in assuming $\|v\|_1 = 1$. Hence,

$$\begin{aligned} D_v(z) &= \sum_{i \notin \Omega} \operatorname{sgn}(z_i)\, v_i + \sum_{i \in \Omega} |v_i| = \sum_{i \notin \Omega} \operatorname{sgn}(z_i)\, v_i \\ &= -\textstyle\sum_{i \notin \Omega} \operatorname{sgn}(z_i)(-v_i) = -D_{-v}(z). \end{aligned}$$

This implies that $D_v(z) = D_{-v}(z) = 0$. Indeed, if not, then one must be negative. Without loss of generality, assume $D_v(0) < 0$. Then the definition of $D_v(z)$ requires that $\|\beta v - z\|_1 < \|z\|_1$ for small $\beta > 0$. This contradicts the l^1 optimality of 0. Now, for $|\lambda|$ sufficiently small, $\lambda v \in W$ and therefore $\operatorname{sgn}(z_i) = \operatorname{sgn}(z_i - \lambda v_i)$, for all $i \notin \Omega$. Thus,

$$\begin{aligned}
\|z - \lambda v\|_1 &= \sum_{i=1}^{n} |z_i - \lambda v_i| = \sum_{i \notin \Omega} |z_i - \lambda v_i| \\
&= \sum_{i \notin \Omega} \operatorname{sgn}(z_i - \lambda v_i)(z_i - \lambda v_i) = \sum_{i \notin \Omega} \operatorname{sgn}(z_i)(z_i - \lambda v_i) \\
&= \|z\|_1 - \lambda D_v(z) = \|z\|_1,
\end{aligned}$$

implying that $\lambda v \in L$. ∎

Directional derivatives provide a bound on the approximation error, $\|x - z\|_1$, near L as follows:

LEMMA 5. *Let $w \in L \cap W$, $v \in V$ with $\|v\|_1 = 1$, and $D = \min(D_v(z), D_{-v}(z))$. Then $D \geqslant 0$ and*

$$\theta(\lambda) = \frac{\|z - w + \lambda v\|_1 - \|z - w\|_1}{|\lambda|} \geqslant D.$$

Proof. Note that if $D < 0$, one of the directional derivatives would be negative. As in Lemma 4, this would contradict the l^1 optimality of 0. Fix $\lambda > 0$ and let $0 < t \leqslant 1$ hold. Then,

$$\begin{aligned}
\|z - w + t\lambda v\|_1 - \|z - w\|_1 &= \|t(z - w + \lambda v) + (1 - t)(z - w)\|_1 - \|z - w\|_1 \\
&\leqslant t\,\|z - w + \lambda v\|_1 + (1 - t)\|z - w\|_1 - \|z - w\|_1 \\
&= t(\|z - w + \lambda v\|_1 - \|z - w\|_1).
\end{aligned}$$

Hence,

$$\begin{aligned}
\|z - w + \lambda v\|_1 - \|z - w\|_1 &= \lambda \lim_{\lambda t \to 0^+} \frac{\|z - w + \lambda t v\|_1 - \|z - w\|_1}{\lambda t} \\
&= \lambda D_v(z - w) = \lambda D_v(z).
\end{aligned}$$

Thus, for $\lambda > 0$ then $\theta(\lambda)/|\lambda| \geqslant D_v(z) \geqslant D$ holds. Likewise, for the case $\lambda < 0$ essentially the same argument shows that $\theta(\lambda)/|\lambda| \geqslant D_{-v}(z) \geqslant D$ holds. ∎

Note that Lemma 5 is a directional strong uniqueness result at w in the direction of $v \in V$ whenever $D > 0$ holds. That is,

$$\|z - w + \lambda v\|_1 \geqslant \|z - w\|_1 + D\|w - \lambda v - w\|_1$$

holds for all $|\lambda|$ sufficiently small. For the special case of $w=0$, this has the form

$$\|z+\lambda v\|_1 \geqslant \|z\|_1 + D\|\lambda v\|_1.$$

If $D=0$, then no such directional strong uniqueness result exists. In fact, if $D=0$ occurs, then for small $\lambda>0$ both λv and $-\lambda v$ are in L. Indeed, suppose that $D_v(z)=0$. Then for $\lambda>0$ sufficiently small, $-\lambda v \in W$ so that

$$\begin{aligned}\|z+\lambda v\|_1 &= \sum_{i \notin \Omega} \operatorname{sgn}(z_i)(z_i+\lambda v_i) + \lambda \sum_{i \in \Omega} |v_i| \\ &= \|z\|_1 + \lambda \sum_{i \notin \Omega} \operatorname{sgn}(z_i)\, v_i + \lambda \sum_{i \in \Omega} |v_i| \\ &= \|z\|_1 + \lambda D_v(z) = \|z\|_1.\end{aligned}$$

Hence, $-\lambda v \in L$ and since 0 is in the relative interior of L, it follows that λv must be in L for sufficiently small $\lambda>0$. Thus, the lack of a local directional strong uniqueness estimate in this case corresponds to approaching 0 through L locally. On the other hand, if v is perpendicular to $K=\operatorname{span}(L)$ then a directional strong uniqueness estimate at 0 in the direction of v will hold. Rephrased, this implies that the approximation error must grow no more slowly than some fixed linear rate for all directions in $K^{\perp}$. This is established in Lemma 6.

LEMMA 6. *For arbitrary* w *and* v *satisfying* $w \in W \cap L$, $v \in V$, *with* $\|v\|_1 = 1$ *and* $v \perp K$, *there exists* $k_0 > 0$ *such that*

$$\|z-w+\lambda v\|_1 \geqslant \|z-w\|_1 + k_0\,|\lambda| \qquad \textit{for each} \quad \lambda \in \mathbb{R}.$$

Proof. For $\lambda \neq 0$ Lemma 5 implies that

$$\|z-w+\lambda v\|_1 - \|z-w\|_1 \geqslant |\lambda|\, D.$$

Now, we claim that there exists $k_0>0$ such that $D \geqslant k_0$ for all $v \in V$ with $\|v\|_1 = 1$ and $v \perp K$. Indeed, assume that $D=D_v(z)$ without loss of generality. If D is not uniformily bounded away from zero we may construct a convergent sequence v_n from V such that $\|v_n\|_1 = 1$, $v_n \perp K$, and $D_{v_n}(z) < 1/n$. Suppose $\lim_{n \to \infty} v_n = v^*$, which can be realized by passing to subsequences if necessary. Then $v^* \in V$, $v^* \perp K$, and $\|v^*\|_1 = 1$. We claim that $D_{v^*}(z)=0$. To see this, let $x \in V$. Then

$$D_x(z) = \sum_{i \in \Omega} |x_i| + \sum_{i \in \Gamma_x} |x_i| - \sum_{i \in \Psi_x} |x_i| + \sum_{i \in \Delta_x} |x_i|,$$

where $\Gamma_x = \{i: x_i z_i > 0\}$, $\Psi_x = \{i: x_i z_i < 0\}$, and $\Delta_x = \{i: i \notin \Omega \text{ and } x_i = 0\}$. Of course the final term contributes 0 to the expression. For large n, $\Gamma_{v^*} = \Gamma_{v_n}$ and $\Psi_{v^*} = \Psi_{v_n}$ so that

$$D_{v_n}(z) = \sum_{i\in\Omega} |v_{ni}| + \sum_{i\in\Gamma_{v^*}} |v_{ni}| - \sum_{i\in\Psi_{v^*}} |v_{ni}| + \sum_{i\in\Delta_{v^*}} \pm |v_{ni}|$$

and

$$D_{v^*}(z) = \sum_{i\in\Omega} |v_i^*| + \sum_{i\in\Gamma_{v^*}} |v_i^*| - \sum_{i\in\Psi_{v^*}} |v_i^*| + \sum_{i\in\Delta_{v^*}} |v_i^*|.$$

This implies that $|D_{v_n}(z) - D_{v^*}(z)| \leqslant \|v_n - v^*\|_1$. Hence $D_{v^*}(z) = 0$. Then, as in the comments following Lemma 5, $\lambda v^* \in L$ for small $|\lambda|$. This contradicts the fact that $v^* \perp K$. The result now follows, since both v and $-v$ satisfy the hypotheses. ∎

As before, let x^p be the best l^p approximation from V to z. Let w^p and v^p be the projections of x^p onto K and $K^\perp$, respectively. Then $x^p = w^p + v^p$. We will require the following inequalities:

LEMMA 7. *There exist constants k_0, k_2, and k_3 so that for small $p > 1$ and $\delta = p - 1$,*

$$0 \geqslant k_0 \|v^p\|_1 + \delta\{n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2\} - k_3\{\|w^p\|_1 + \|v^p\|_1\} \delta^2.$$

Proof. On $W \cap L$, $\psi(v) = \sum_{i=1}^n |v_i - z_i| \ln |v_i - z_i|$ reduces to $\psi(v) = \sum_{i\in\Omega^c} |v_i - z_i| \ln |v_i - z_i|$, where $|v_i - z_i| > \varepsilon$ for each $i \in \Omega^c$. Since 0 is in the relative interior of the polyhedral set L there exists ζ, $\rho > \zeta > 0$, so that the set $Q = \{v: v \in K, \|v\|_1 < \zeta\} \subseteq L$, where ρ is from Lemma 2. Write $\Omega^c = \Omega^+ \cup \Omega^-$, where $z_i > 0$ on Ω^+ and $z_i < 0$ on Ω^-. For $v \in K$, with $\|v\|_1 = 1$, compute the derivatives of $\psi(tv)$ for $|t| < \zeta$.

$$\begin{aligned}\frac{d}{dt}\psi(tv) &= \frac{d}{dt}\sum_{\Omega^c} |tv_i - z_i| \ln |tv_i - z_i| \\ &= \frac{d}{dt}\sum_{i\in\Omega^+} (z_i - tv_i) \ln (z_i - tv_i) + \frac{d}{dt}\sum_{i\in\Omega^-} (tv_i - z_i) \ln (tv_i - z_i) \\ &= \sum_{i\in\Omega^+} -v_i[\ln(z_i - tv_i) + 1] + \sum_{i\in\Omega^-} v_i[\ln(tv_i - z_i) + 1],\end{aligned}$$

and

$$\frac{d^2}{dt^2}\psi(tv) = \sum_{i\in\Omega^+} \frac{v_i^2}{(z_i - tv_i)} + \sum_{i\in\Omega^-} \frac{v_i^2}{(tv_i - z_i)}.$$

Evaluating this expression at $t=0$ yields

$$\frac{d^2}{dt^2}\psi(tv)\,|_{t=0}=\sum_{i\in\Omega^c}\frac{v_i^2}{|z_i|}.$$

Hence there exists $k_1>0$ such that for $v\in K$ and $\|v\|_1$ sufficiently small, $\psi(v)\geqslant k_1\,\|v\|_1^2$. Since $x^p\to 0$, we know that $w^p\in Q\subseteq L$ for p near 1. Then, for such values of p, Lemma 6 implies that

$$\|x^p-z\|_1-\|z\|_1=\left\|w^p+\|v^p\|_1\left(\frac{v^p}{\|v^p\|_1}\right)-z\right\|_1-\|w^p-z\|_1\geqslant k_0\,\|v^p\|_1. \quad (1)$$

Similarly, for small $p>1$, there exists $k_2>0$ such that $\psi(x^p)-\psi(0)\geqslant n\,\|v^p\|_1\ln\|v^p\|_1+k_2\,\|w^p\|_1^2$. Indeed, by previous scaling $\|z\|_1\leqslant 1/(2e^2)$. Set $\alpha=\min\{|z_i|: i\in\Omega^c\}$. Then $\alpha>0$ and there exists $p_0>1$ such that $p_0>p>1$ implies that $w^p\in Q$ and $\max_{1\leqslant j\leqslant n}\{|x_j^p|, |v_j^p|, |w_j^p|\}<(\alpha/10)$. Thus for any index $i\notin\Omega$ we have that

$$0.9\alpha<\max_i\,\{|z_i-x_i^p|, |z_i-v_i^p|, |z_i-w_i^p|\}<1/e^2.$$

The desired inequality follows from the fact that both $g(x)=-x\ln x$ and $h(x)=x\ln^2 x$ are strictly increasing on $[0, 1/e^2]$. To see this, observe that for such p

$$\psi(x^p)=\sum_{\Omega}|v_i^p|\ln|v_i^p|+\sum_{\Omega^c}|x_i^p-z_i|\ln|x_i^p-z_i|.$$

This implies that

$$\begin{aligned}\psi(x^p)-\psi(0)=&\sum_{\Omega}|v_i^p|\ln|v_i^p|\\&+\sum_{\Omega^c}\{|x_i^p-z_i|\ln|x_i^p-z_i|-|w_i^p-z_i|\ln|w_i^p-z_i|\}\\&+\sum_{\Omega^c}\{|w_i^p-z_i|\ln|w_i^p-z_i|-|z_i|\ln|z_i|\}. \quad (2)\end{aligned}$$

In the second summation, the Mean Value Theorem implies that there exists c_i^p between x_i^p and w_i^p such that

$$\sum_{\Omega^c}\{|x_i^p-z_i|\ln|x_i^p-z_i|-|w_i^p-z_i|\ln|w_i^p-z_i|\}=\sum_{\Omega^c}(1+\ln|z_i-c_i^p|)\,v_i^p.$$

Since $\ln \|v^p\| \to -\infty$ there exists p_1, with $p_0 > p_1 > 1$, such that for $p_1 > p > 1$ and $i \in \Omega^c$ it follows that $1 + \ln |z_i - c_i^p| \geqslant \ln \|v^p\|_1$. Hence, for $p_1 > p > 1$, the first two summations in (2) yield

$$\sum_{\Omega} |v_i^p| \ln |v_i^p| + \sum_{\Omega^c} \{|x_i^p - z_i| \ln |x_i^p - z_i| \\ - |w_i^p - z_i| \ln |w_i^p - z_i|\} \geqslant n \|v^p\|_1 \ln \|v^p\|_1. \tag{3}$$

Consider now the final summation in (2). Since $w^p \in L$ the function $\psi(tw^p)$ has a local minimum at $t = 0$ and

$$\psi(w^p) - \psi(0) = \sum_{\Omega^c} \{|w_i^p - z_i| \ln |w_i^p - z_i| - |z_i| \ln |z_i|\} = \frac{1}{2} \sum_{\Omega^c} \frac{(w_i^p)^2}{|z_i - \gamma_i w_i^p|},$$

for some set γ_i, $0 < \gamma_i < 1$. The final term above is just the remainder term of a first order Taylor expansion for $\psi(w^p)$ expanded about $t = 0$. Hence, using the equivalence of norms on $\mathbb{R}^n$ implies that the final summation satisfies

$$\psi(w^p) - \psi(0) \geqslant k_2 \|w^p\|_1^2 \tag{4}$$

for some $k_2 > 0$. Combining (3) and (4) yields

$$\psi(x^p) - \psi(0) \geqslant n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2. \tag{5}$$

We now bound the difference $\|x^p - z\|_p^p - \|z\|_p^p$. By the p-norm optimality of x^p this difference must be negative. Now expand $\|z\|_p^p$ and $\|x^p - z\|_p^p$ into Taylor series about 1 to obtain

$$\|x^p - z\|_p^p = \|x^p - z\|_1 + \delta\psi(x^p) + \frac{\delta^2}{2} \ln^2 |x_i^p - z_i| \\ + \delta^2 \sum_{r=2}^{\infty} \frac{\delta^{r-2}}{r!} \sum_{\Omega^c} |x_i^p - z_i| \ln^r |x_i^p - z_i| \tag{6}$$

and

$$\|z\|_p^p = \|z\|_1 + \delta\psi(0) + \frac{\delta^2}{2} \ln^2 |z_i| + \delta^2 \sum_{r=2}^{\infty} \frac{\delta^{r-2}}{r!} \sum_{\Omega^c} |z_i| \ln^r |z_i|, \tag{7}$$

where $\delta = p - 1$ and the convergence in each series in uniform. To subtract (7) from (6) consider first the difference in the $\|\cdot\|_1$ terms. By (1),

$\|x^p - z\|_1 - \|z\|_1 \geqslant k_0 \|v^p\|_1$. Similarly, (5) bounds the $\delta\psi$ terms. To bound the series terms invoke the Mean Value Theorem to get

$$\delta^2 \sum_{r=2}^{\infty} \left[\frac{\delta^{r-2}}{r!} \sum_{\Omega^c} |x_i^p - z_i| \ln^r |x_i^p - z_i| - |z_i| \ln^r |z_i| \right]$$
$$= \delta^2 \sum_{r=2}^{\infty} \left[\frac{\delta^{r-2}}{r!} \sum_{\Omega^c} (\ln^r |\theta_i x_i^p - z_i| + r \ln^{r-1} |\theta_i x_i^p - z_i|) \, x_i^p \right]$$

for some set θ_i, $0 < \theta_i < 1$. By our restrictions on p, $|\theta_i x_i^p - z_i| \geqslant 4\alpha/5$. Hence there exists $k_3 > 0$ such that the above difference is bounded above by $k_3 \|x^p\|_1 \delta^2$. Combining these terms yields

$$\begin{aligned} 0 &\geqslant \|x^p - z\|_p^p - \|z\|_p^p \\ &\geqslant k_0 \|v^p\|_1 + \delta\{n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2\} - k_3(\|x^p\|_1)\, \delta^2. \end{aligned}$$

Since $\|x^p\|_1 \leqslant \|v^p\|_1 + \|w^p\|_1$ we have

$$\begin{aligned} 0 &\geqslant \|x^p - z\|_p^p - \|z\|_p^p \\ &\geqslant k_0 \|v^p\|_1 + \delta\{n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2\} - k_3\{\|w^p\|_1 + \|v^p\|_1\}\, \delta^2, \end{aligned}$$

which is the desired result. ∎

We can now prove the main result of this paper.

THEOREM 2. *The net x^p converges to the natural best approximation at a rate no worse than $O(p-1)$.*

Proof. By Lemma 7, there exist positive constants k_0, k_2, k_3, and $p_1 > 1$ so that if $p_1 > p > 1$,

$$0 \geqslant k_0 \|v^p\|_1 + \delta\{n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2\} - k_3\{\|w^p\|_1 + \|v^p\|_1\}\, \delta^2.$$

By replacing k_0 by some $k_4 > 0$, we may absorb the final term into the first and find $p_2 > 1$ so that for $p_2 \geqslant p > 1$

$$0 \geqslant k_4 \|v^p\|_1 + \delta\{n \|v^p\|_1 \ln \|v^p\|_1 + k_2 \|w^p\|_1^2\} - k_3 \|w^p\|_1 \delta^2$$

and

$$\|v^p\|_1 \leqslant |\ln \|v^p\|_1|$$

hold with the second inequality following from the fact that $\|v^p\|_1 \to 0$ as $p \to 1^+$. Set $\beta = \exp(-k_4/(2n))$ and $\eta = (1+\beta)/2$ and note that $0 < \beta < \eta < 1$ holds. Thus, there exists p_3, $1 < p_3 < \min(p_2, 1 + e^{-1})$, such that

$k_4/(2k_3(p-1)^2) \leqslant (\eta/\beta)^{1/(p-1)}$ and $\eta \leqslant ((p-1)/2)^{p-1}$ hold for $1 < p \leqslant p_3$. Now for a given p, $p_3 > p > 1$, suppose that

$$|n\delta \,\|v^p\|_1 \ln \|v^p\|_1| > k_3 \delta^2 \,\|w^p\|_1 \tag{8}$$

holds. Then $0 \geqslant k_4 \,\|v^p\|_1 + \delta 2n \,\|v^p\|_1 \,\ln \|v^p\|_1 + \delta k_2 \,\|w^p\|_1^2$ and so $0 \geqslant k_4 \,\|v^p\|_1 + \delta 2n \,\|v^p\|_1 \,\ln \|v^p\|_1$. This implies that $\beta^{1/\delta} \geqslant \|v^p\|_1$. Note also that (8) implies that $\beta^{1/\delta} \geqslant (2k_3\delta^2 \,\|w^p\|_1/k_4)$ holds since $|x \ln x|$ is increasing on $(0, e^{-1})$. Thus, η satisfies $\eta^{1/\delta} \geqslant \|v^p\|_1$ and

$$\eta^{1/\delta} = (\eta/\beta)^{1/\delta} \,\beta^{1/\delta} \geqslant (\eta/\beta)^{1/\delta} \,(2k_3\delta^2 \,\|w^p\|_1/k_4) \geqslant \|w^p\|_1.$$

From this it follows that x^p, corresponding to this p, satisfies $\|x^p\|_1 \leqslant \|v^p\|_1 + \|w^p\|_1 \leqslant 2\eta^{1/\delta}$. Since x^x is decreasing from 1 on $(0, e^{-1})$ it follows by the restrictions placed on η and p_3 above that $\|x^p\|_1 \leqslant \delta$ also holds in this case.

On the other hand, if (8) does not hold for a given p, $1 < p < p_3$, then

$$|n\delta \,\|v^p\|_1 \ln \|v^p\|_1| \leqslant k_3 \delta^2 \,\|w^p\|_1$$

implies $0 \geqslant k_4 \,\|v^p\|_1 + \delta k_2 \,\|w^p\|_1^2 - 2k_3 \,\|w^p\|_1 \,\delta^2$ and hence $0 \geqslant k_2 \,\|w^p\|_1 - 2k_3\delta$. Thus, $\|w^p\|_1$ is $O(\delta)$. In this case we also have by our choice of p_2 that

$$\|v^p\|_1^2 \leqslant \|v^p\|_1 \,|\ln \|v^p\|_1| \leqslant k_3\delta \,\|w^p\|_1/n$$

so that $\|v^p\|_1$ is $O(\delta)$ and $\|x^p\|_1$ is $O(\delta)$, $\delta = p-1$, as desired. ∎

Note that if (8) holds for all p near 1 then convergence of at least exponential rate holds. This must always be the case if $x^p \perp K$ for all p sufficiently close to 1. This yields the following theorem:

THEOREM 3. *If $x^p \perp K$ for all p sufficiently close to* 1 *then there exists γ, $1 > \gamma > 0$, such that x^p converges to the natural best approximation at a rate no worse than $O(\gamma^{1/(p-1)})$.*

For the special case in which L is a singleton, Theorem 3 yields the following:

COROLLARY 1. *If L is a singleton there exists γ, $1 > \gamma > 0$, such that x^p converges to the natural best approximation at a rate no worse than $O(\gamma^{1/(p-1)})$.*

The examples given earlier illustrate these rates and show the rates to be sharp. The following example shows that these results need not hold in general finite dimensional L^1 subspace approximation problems.

EXAMPLE 3. Consider the 1-dimensional problem of approximating $f(x)=1$ on $[0, 1]$ from the subspace of functions $V=\{ax: a \in \mathbb{R}\}$. For $p>1$ it is immediate that there exists a unique best approximation $x^p = a^p x$. That is,

$$\int_0^1 |a^p x - 1|^p \, dx = \min_{a \in \mathbb{R}} \int_0^1 |ax-1|^p \, \mathrm{dx}.$$

Furthermore, it is easily seen that $a^p \geqslant 1$ for $p>1$. Thus, finding best approximations is equivalent to minimizing $H_p(r)$, $r \geqslant 1$, $p \geqslant 1$, where

$$\begin{aligned} H_p(r) &= \int_0^1 |rx-1|^p \, dx \\ &= \int_0^{1/r} (1-rx)^p \, dx + \int_{1/r}^1 (rx-1)^p \, dx = \frac{(1+(r-1)^{p+1})}{(p+1)r}. \end{aligned}$$

Now $H_p'(r) = (-1+(pr+1)(r-1)^p)/((p+1)\, r^2)$. Thus, for $p=1$, it is easily seen that the problem,

$$\min_{r \geqslant 1} \int_0^1 |rx-1| \, dx,$$

has a unique solution $a^1=\sqrt{2}$. Since $a^p \to a^1$, we need only consider $1.4 \leqslant r \leqslant 1.5$ for small $p \geqslant 1$. For small $p \geqslant 1$, a^p is a solution to $(pr+1)(r-1)^p - 1 = 0$. Note that

$$\begin{aligned} (pr+1)(r-1)^p - 1 &= (r+1)(r-1)(r-1)^{p-1} - 1 + (p-1)\, r(r-1)^p \\ &= [(r+1)(r-1)](1-(2-r))^{p-1} \\ &\quad - 1 + (p-1)\, r(r-1)^p. \end{aligned}$$

Applying the Mean Value Theorem to $(1-x)^{p-1}$ then yields

$$\begin{aligned} (pr+1)(r-1)^p - 1 &= (r+1)(r-1)[1-(p-1)(1-\zeta)^{p-2}(2-r)] - 1 \\ &\quad + (p-1)\, r(r-1)^p, \end{aligned}$$

where ζ is between 0 and $2-r$. For the values of r of interest, $0 \leqslant \zeta \leqslant 0.6$ since $1.4 \leqslant a^p \leqslant 1.5$ here. Thus, for small $p \geqslant 1$, $(1-\zeta)^{p-2} \in [1, 2.5]$, $(1-\zeta)^{p-2}(2-a^p) \in [0.5, 1.5]$, and $a^p(a^p-1)^p \in [(1.4)(0.4)^{3/2}, (1.5)(0.5)^{3/2}] \subseteq [0.3, 0.75]$. Now $H_p'(a^p)=0$ implies that

$$\begin{aligned} 0 &= (pa^p+1)(a^p-1)^p - 1 \\ &= (a^p+1)(a^p-1)[1-(p-1)(1-\zeta)^{p-2}(2-a^p)] \\ &\quad - 1 + (p-1)\, a^p(a^p-1)^p. \end{aligned}$$

Hence

$$(a^p+1)(a^p-1)-1=(p-1)([(a^p)^2-1](1-\zeta)^{p-2}(2-a^p)-a^p(a^p-1)^p)$$
$$=(p-1)\,\omega^p.$$

Using the above estimates, ω^p, defined in the previous equation, can be seen to be bounded. That is, there exist positive constants C and D such that $C \leqslant \omega^p \leqslant D$. Now $(a^p)^2 = 2+(p-1)\,\omega^p$ and so that $a^p = (2+(p-1)\,\omega^p)^{1/2}$. Finally, expanding $(1+\alpha)^{1/2}$ we may write $a^p = \sqrt{2}+(p-1)\,\gamma^p$ where there exist positive constants J and K with $J < \gamma^p < K$. Thus, we have a linear rate of convergence even through L is a singleton.

It remains open whether this rate holds in general in $C[0, 1]$, or whether even slower convergence may occur. Also open is the question of the effect of constraints on the rate of convergence. The Pólya-1 algorithm is known to converge as long as the approximating set is convex. However, it is not know whether the imposition of constraints slows or accelerates convergence.

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